AN EXTENSION OF THE SIMULTANEOUS TOVS RETRIEVAL ALGORITHM - THE INCLUSION OF CLOUD PARAMETERS

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1. INTRODUCTION

A direct simultaneous solution of the radiative transfer equation for temperature, water vapor and surface skin temperature (Smith, et al., 1984) is used by Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the University of Wisconsin-Madison for routine processing of VAS and TOVS data. An evaluation of retrieval results from VAS and TOVS data indicate significant improvements in the water vapor profile and small, but significant improvements for temperature profiling (Jedlovec, 1985; Smith et al., 1985). Despite these recent improvements, retrieval quality still suffers from the contamination of the sounding radiances by cloud (Susskind et al., 1982; Wielicki and Coakley, 1981). Hence an extension of the simultaneous retrieval algorithm to include cloud parameters is formulated to improve the retrieval of temperature and water vapor profiles, and surface skin temperature in cloudy situations. The extension enables the simultaneous retrieval of cloud amount and cloud top temperature with the atmospheric profiles from polar orbiting satellite TIROS Operational Vertical Sounder (TOVS) spectral radiance observations.

The results have been compared with those of the original simultaneous retrieval algorithm for the ALPine EXperiment (ALPEX) orbits (March 4 and 5, 1982). The comparison between the retrieval results and European Center for Medium Range Weather Forecasting (ECMWF) analyses of radiosonde data indicate significant improvements of temperature profile accuracy for both regression and climatology based guess for all weather conditions. The results of this extended algorithm using a regression guess show a very large improvement for moderate and heavy cloud conditions.

2. EXTENDED SIMULTANEOUS PHYSICAL RETRIEVAL SOLUTION

The radiative transfer equation for the cloudy FOV can be expressed by,

$$I = (1-N)[B_s\tau_s - \int_o^{p_s} B\frac{d\tau}{dp}dp] + N[B_c\tau_c - \int_o^{p_c} B\frac{d\tau}{dp}dp] \qquad (1)$$

where the cloud pressure is p_c, the effective cloud amount is N, the cloud top temperature is T_c, transmittance at cloud level is τ_c, and the temperature and transmittance at the surface is T_s and τ_s, respectively (Fig. 1).

The dependence on wavelength of Eq.(1) and the pressure dependence of all integrand variables are to be understood. Equation (2) is written in perturbation form,

$$\delta T^* = [(1-N)\tau_s \frac{(\partial B_s/\partial T_s)}{(\partial B/\partial T^*)} \delta T_s] + [N\tau_c \frac{(\partial B_c/\partial T_c)}{(\partial B/\partial T^*)} \partial T_c]$$

$$+ [N \int_{P_c}^{P_s} \delta T \frac{\partial \tau}{\partial P} \frac{(\partial B/\partial T)}{(\partial B/\partial T^*)} dP - \int_{o}^{P_s} \delta T \frac{\partial \tau}{\partial P} \frac{(\partial B/\partial T)}{(\partial B/\partial T^*)} dP]$$

$$+ [\int_{o}^{P_s} \delta U \frac{\partial \tau}{\partial U} \frac{\partial T}{\partial P} \frac{(\partial B/\partial T)}{(\partial B/\partial T^*)} dP - N \int_{P_c}^{P_s} \delta U \frac{\partial \tau}{\partial U} \frac{\partial T}{\partial P} \frac{(\partial B/\partial T)}{(\partial B/\partial T^*)} dP]$$

$$+ [B_c \tau_c \frac{1}{(\partial B/\partial T^*)} - B_s \tau_s \frac{1}{(\partial B/\partial T^*)} + \int_{P_c}^{P_s} B \frac{\partial \tau}{\partial P} \frac{1}{(\partial B/\partial T^*)} dP] \delta N \qquad (2)$$

Here it has been assumed that the cloud pressure is prescribed, however, cloud pressure is to be updated through its relation to cloud top temperature.

The unknowns of Eq.(2) are δT_s, the perturbation of surface temperature, δT_c, the perturbation of cloud top temperature, δT, the perturbation of temperature profile, δU, the perturbation of precipitable water profile, and δN, the perturbation of effective cloud amount. Since the unknowns δT and δU are too numerous to be solved for directly, a small set of basis functions is assumed to represent the profiles. The basis functions are

$$\delta U(P) = \sum_{i=1}^{3} \alpha_i \int_{o}^{P} q_o(P) \frac{\partial \tau}{\partial \ln P} dP \qquad (3a)$$

$$\delta T(P) = -\sum_{i=4}^{9} \alpha_i \frac{\partial \tau}{\partial \ln P} dP \qquad (3b)$$

$$\delta T_s = \alpha_i \ ; \ i = 10 \qquad (3c)$$

$$\delta N = \alpha_i \ ; \ i = 11 \qquad (3d)$$

$$\delta T_c = \alpha_i \ ; \ i = 12 \qquad (3e)$$

where the zero subscript indicates the a priori condition. Substituting equation 3(a-e) into equation (2), yields for each spectral radiance observation, δT^*_j, for a set of K spectral channels and k+1 and k+2 ancillary surface temperature and mixing ratio data.

$$\delta T_j^* = \sum_{i=1}^{12} \alpha_i \Phi_{ij} \; ; \; j = 1, 2, \ldots K, K+1, K+2 \tag{4}$$

The α_i's are the explicit coefficients which need to be solved for to achieve the solution, K is the number of spectral channels used, and K+1, K+2 refer to ancillary surface temperature and water vapor data included to improve the retrieval results.

In Eq.(4), $\Phi_{i,j}$ are given by,

$$\Phi_{ij} = \int_o^{P_s} \left(\int_o^{P} q_o(P) \left(\frac{\partial \tau_i}{\partial \ln p}\right) dp\right) \frac{\partial \tau_j}{\partial U} \frac{\partial T}{\partial P} \frac{\partial B_j/\partial T)}{(\partial B_j/\partial T_j^*)} dp$$

$$-N\int_{P_c}^{P_s} \left(\int_o^{P} q_o(P) \left(\frac{\partial \tau_i}{\partial \ln p}\right) dp\right) \frac{\partial \tau_j}{\partial U} \frac{\partial T}{\partial P} \frac{\partial B_j/\partial T)}{(\partial B_j/\partial T_j^*)} dp \; ; \quad 1 \leq i \leq 3 \tag{4a}$$

$$\Phi_{ij} = \int_o^{P_s} \left(\frac{\partial \tau_i}{\partial \ln p} \frac{\partial \tau_j}{\partial P} \frac{\partial B_j/\partial T)}{\partial B_j/\partial T^*}\right) dp - N\int_{P_c}^{P_s} \left(\frac{\partial \tau_i}{\partial \ln p}\right) \frac{\partial \tau_j}{\partial P} \left(\frac{\partial B_j/\partial T}{\partial B_j/\partial T_j^*}\right) dp \tag{4b}$$

$$; \quad 4 \leq i \leq 9$$

$$\Phi_{ij} = (1-N)\tau_{sj} \frac{(\partial B_{sj}/\partial T_s)}{(\partial B_{sj}/\partial T_j^*)} \; ; \quad i=10 \tag{4c}$$

$$\Phi_{ij} = B_{cj} \tau_{cj} \frac{1}{(\partial B_j/\partial T_j^*)} - B_{sj} \tau_{sj} \frac{1}{(\partial B_j/\partial T_j^*)}$$

$$+ \int_{P_c}^{P_s} B_j \frac{\partial \tau_j}{\partial P} \frac{1}{(\partial B_j/\partial T_j^*)} dp \quad ; \; i=11 \tag{4d}$$

$$\Phi_{ij} = N\tau_{cj} \frac{(\partial B_{cj}/\partial T_c)}{(\partial B_{cj}/\partial T_j^*)} \quad ; \; i=12 \tag{4e}$$

In Eq.(4), the quantities $\Phi_{i,j}$ are calculated from the a priori estimates or mean profile conditions.

In solving Eq.(4), the conditional least squares solution is used,

$$[\alpha]_{12} \cong ([\Phi]^T[\Phi] + r[I])^{-1}[\Phi]^T[\delta T^*] \quad . \tag{5}$$

where $[\ ]^T$ indicates matrix transposition, and $(\ )^{-1}$ indicates matrix inversion. Letter r is a scalar (0.1 is used for the clear condition, and 1.0 is used for the cloudy condition). [I] is the identity matrix, r[I] is incorporated to stabilize the matrix inversion. Once $[\alpha]_{12}$ is determined, $\delta U(p)$, $\delta T(p)$, δT_s, δN and δT_c can be calculated and added to the a priori estimates to yield the final solution.

3. RETRIEVAL LOGISTICS

The simultaneous retrieval method has been used at CIMSS for routine processing of both Polar Orbiting (TOVS) and Geostationary (VAS) satellite soundings since 1984. Since then, related papers and reports have been presented at two International TOVS study conferences and detailed descriptions of the retrieval algorithm and logistics have been published (Smith et al., 1984, Smith, Woolf, 1984, Smith et al., 1985). In this study, only the retrieval procedures which differ from the CIMSS's operation package are discussed.

Figure 2 shows the flow diagram for the extended (modified) simultaneous retrieval procedure. After HIRS and MSU data are amalgamated and one set of retrieval radiances have been calculated from the 3 by 3 HIRS FOVs, the CO_2 slicing method (Smith and Platt, 1978, Menzel et al., 1983) is performed and cloud parameters for the initial guess are determined. The extended simultaneous retrieval will then conduct the "step 1" retrieval procedure. The perturbation of cloud top temperature δT_c is checked to see that the cloud height determination does not deviate greatly from the "prescribed" value. If it is too large, "step 1" is repeated to obtain a better first estimate. The "step 2" retrieval is performed to reach the final solution.

For the achievement of the final sounding profiles and parameters, the perturbation of cloud top temperature, δT_c, has to be small to terminate the retrieval process. If δT_c is not small, the "step 2" retrieval is iterated until the convergence criterion is satisfied. The cloud top pressure is obtained by comparing the cloud top temperature with the final temperature profile. The cloud pressure level where the atmospheric temperature is best matched to the retrieval cloud top temperature.

4. RESULTS

To study the impact of the extended simultaneous retrieval algorithm, two sets of retrievals were achieved using two independent initial guess profile procedures; (a) statistical regression guess, and (b) climatology guess. The original simultaneous retrieval algorithm and the extended simultaneous retrievals were compared with conventional analyses of radiosonde data for the March 4, 5, 1982 ALPEX data sets.

Root mean square deviation (RMSD) between TOVS retrievals and ECMWF analyses were produced for the March 4, 5, 1982 cases. Figure 3 shows the RMSD comparison of the original simultaneous and the extended simultaneous methods for the regression guess condition. Improvement is shown at all levels with significant improvement displayed for the 850 mb to 400 mb region and the 250 mb level. Figure 4 displays the same comparison except for climatology first guess condition showing significant temperature improvement below 600 mb. In order to explore the cause of the improvements displayed for the extended (modified) simultaneous retrieval, different sets of statistics have been produced. These statistics are the temperature RMSD values for the three different cloud conditions. Namely, (1) clear or low cloud conditions, (i.e., brightness temperature of HIRS/2 channel 8 TB(8) larger than 270 K), (2) moderate cloudy conditions, (i.e., TB(8) between 250 to 270 K), and (3) heavy cloudy conditions, (i.e., TB(8) smaller than 250 K). Figures 5-7 show the improvements in these three conditions. Clearly, the most significant improvements in the temperature profile retrieval using the extended simultaneous retrieval method are in the cloudy regions.

5. SUMMARY AND CONCLUSIONS

An extended (modified) simultaneous TOVS sounding profile retrieval algorithm has been developed to simultaneously account for the effects of the clouds. The results show significant improvement for retrievals of temperature for the ALPEX data sets of March 4 and 5, 1982. Classification of the statistics reveal the temperature retrieval improvements in different cloud conditions; a) clear or low cloud, small improvement, b) moderate cloudiness, large improvement, and c) heavy cloudiness, very large improvement. As a result of the improvements displayed here the UW-CIMSS is planning to incorporate this method of simultaneously accounting for cloud effects in it's International TOVS Processing Package (ITPP), used by direct readout satellite data producers on a world-wide basis.

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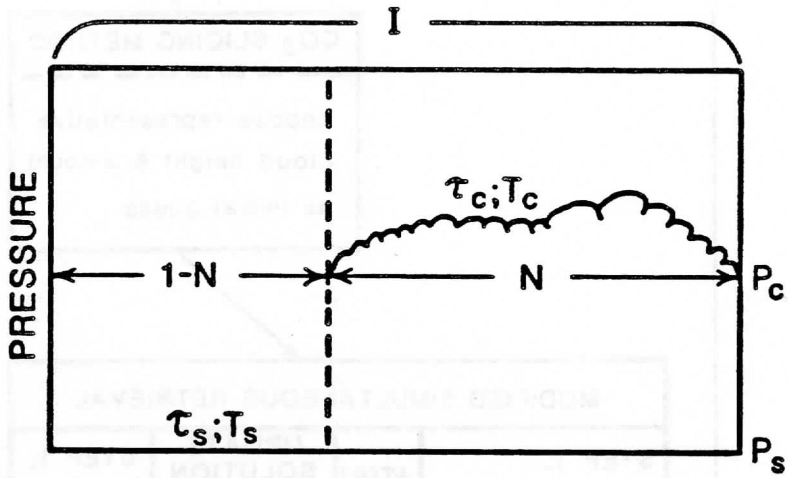
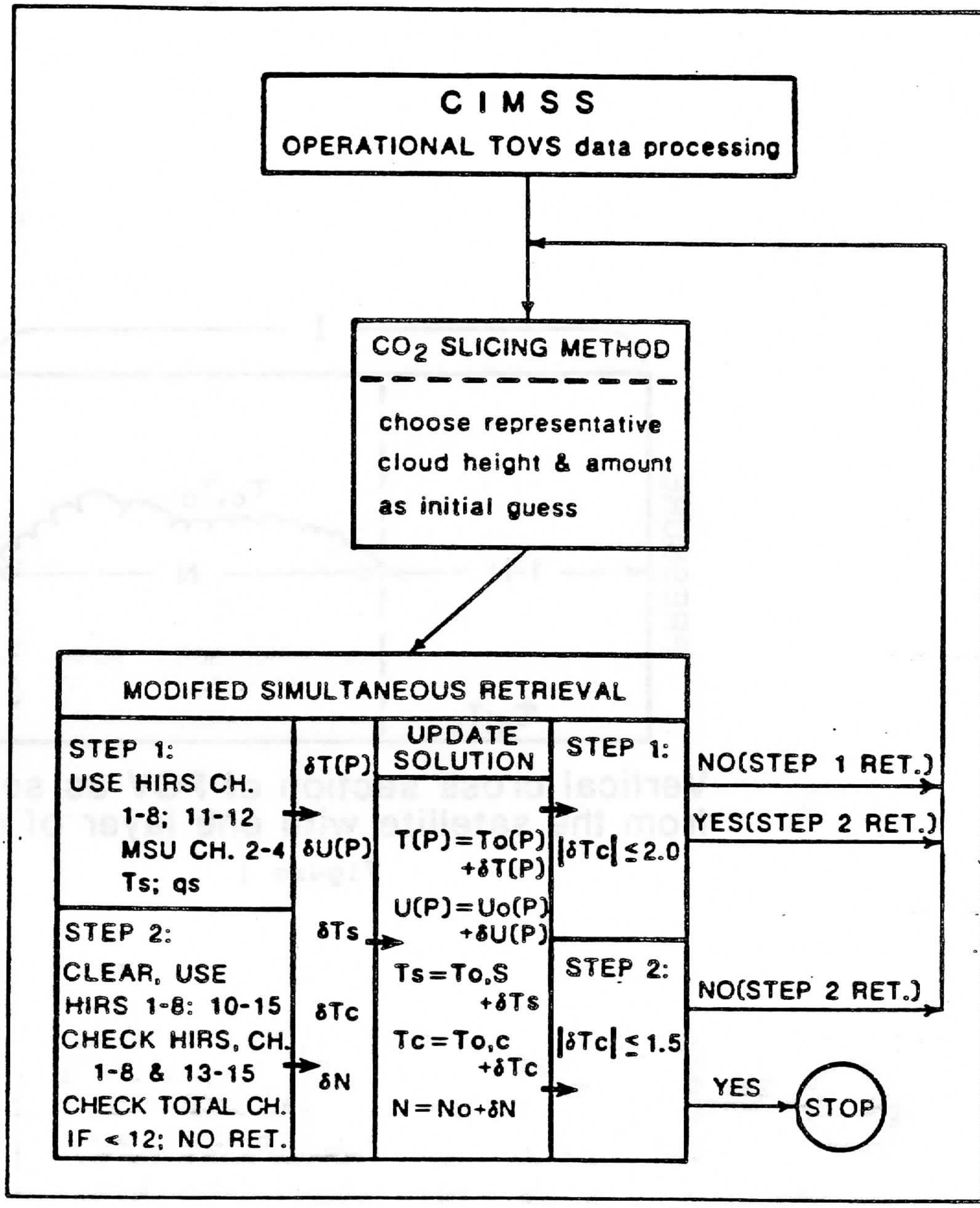


Vertical cross section of FOV as seen from the satellite with one layer of cloud.

Figure 1



Flow diagram for the modified simultaneous retrieval

Figure 2

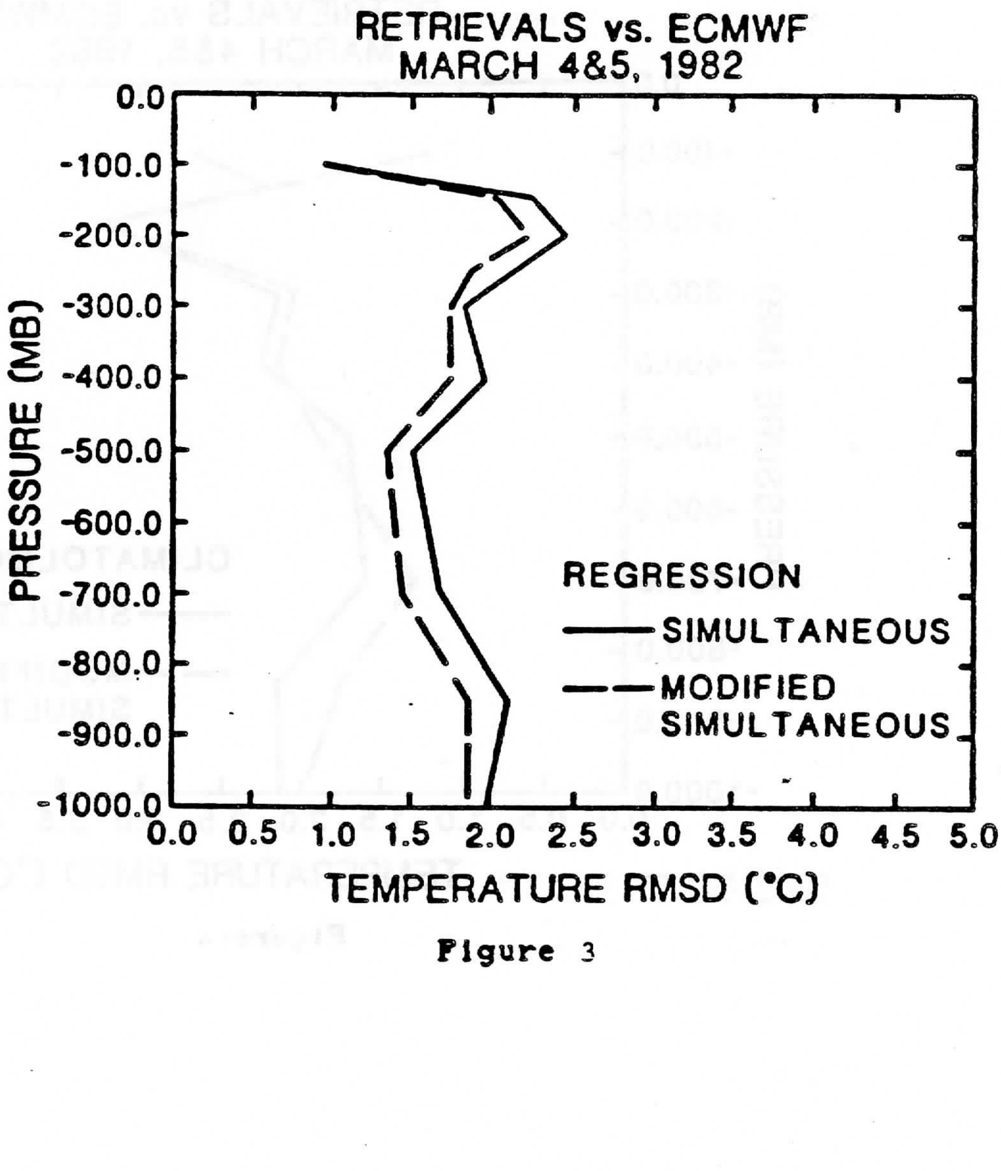

RETRIEVALS vs. ECMWF
MARCH 4&5, 1982
PRESSURE (MB)
0.0
-100.0
-200.0
-300.0
-400.0
-500.0
-600.0
-700.0
-800.0
-900.0
-1000.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
TEMPERATURE RMSD (°C)
REGRESSION
SIMULTANEOUS
MODIFIED
SIMULTANEOUS

Figure 3

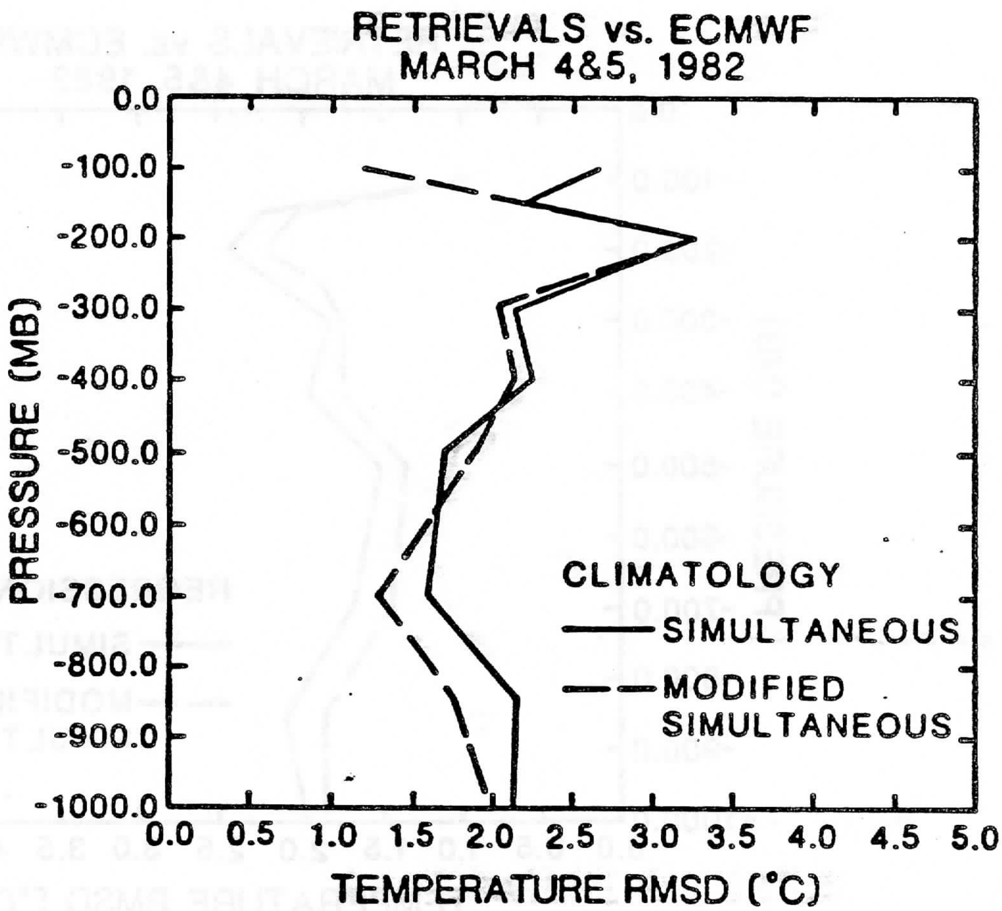

RETRIEVALS vs. ECMWF
MARCH 4&5, 1982
PRESSURE (MB)
0.0
-100.0
-200.0
-300.0
-400.0
-500.0
-600.0
-700.0
-800.0
-900.0
-1000.0
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
TEMPERATURE RMSD (°C)
CLIMATOLOGY
SIMULTANEOUS
MODIFIED SIMULTANEOUS

Figure 4

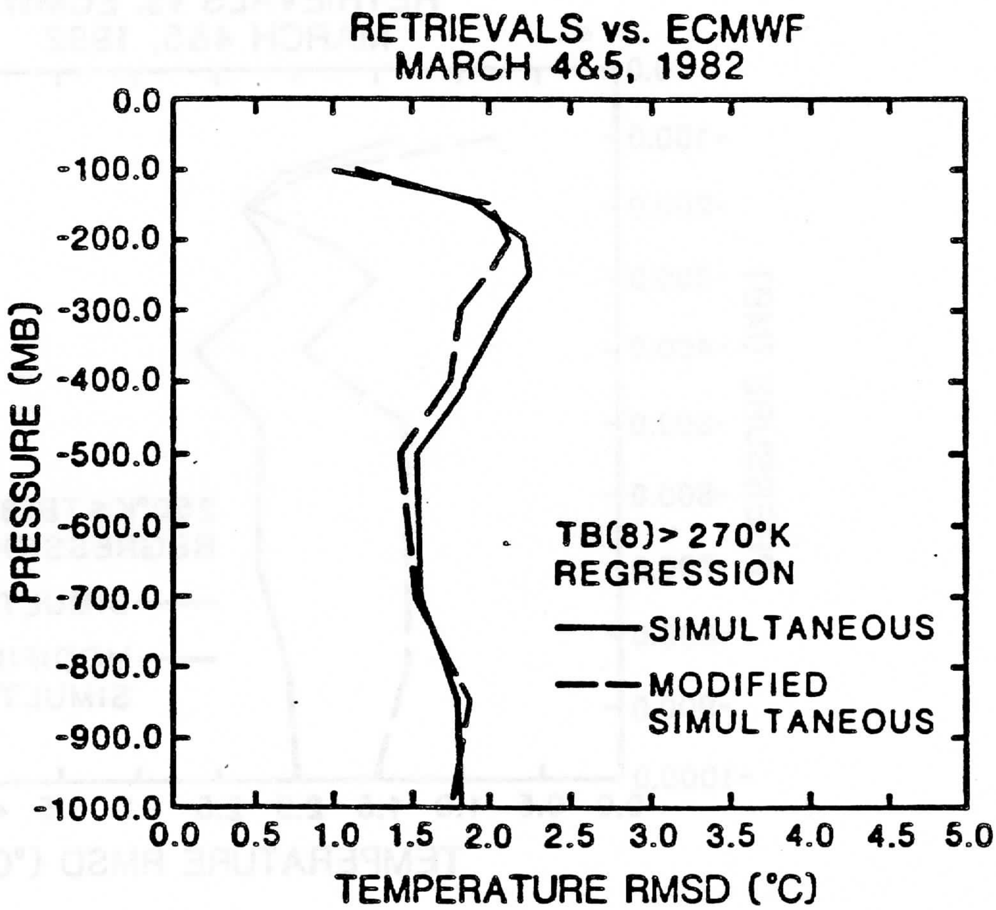
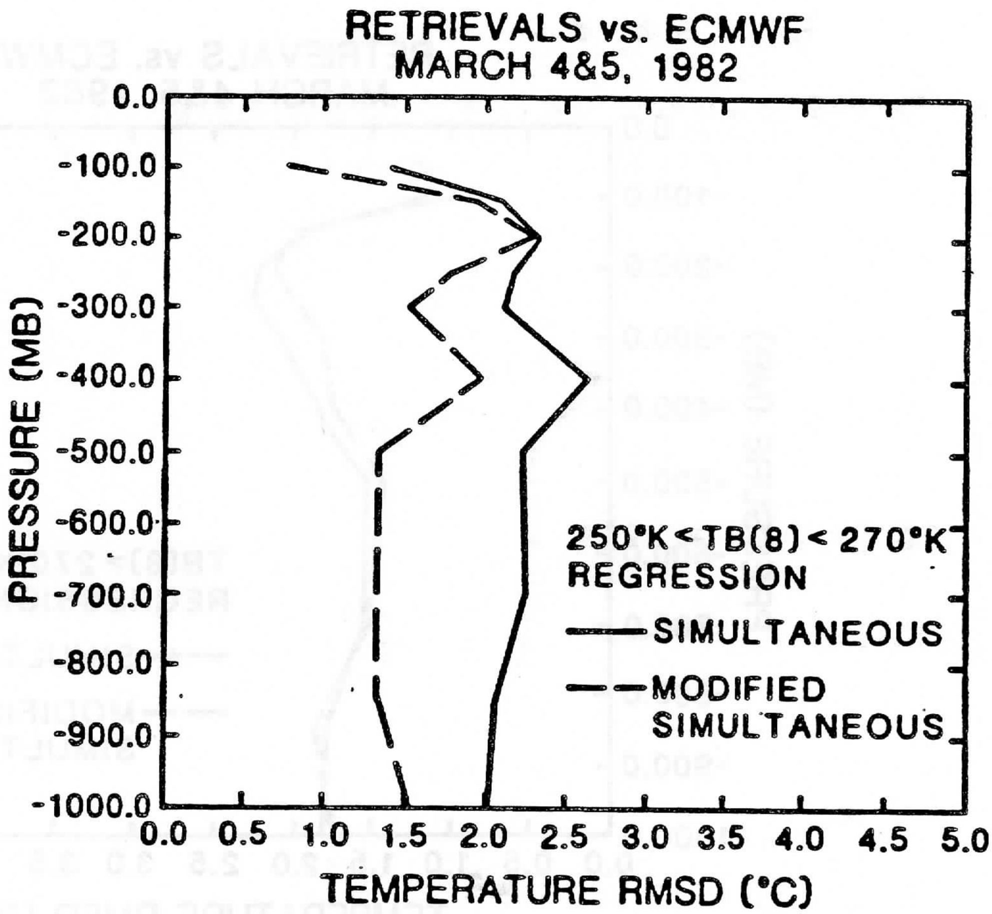

RETRIEVALS vs. ECMWF
MARCH 4&5, 1982
PRESSURE (MB)
0.0
-100.0
-200.0
-300.0
-400.0
-500.0
-600.0
-700.0
-800.0
-900.0
-1000.0
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
TEMPERATURE RMSD (°C)
TB(8)> 270°K
REGRESSION
SIMULTANEOUS
MODIFIED SIMULTANEOUS

Figure 5



RETRIEVALS vs. ECMWF
MARCH 4&5, 1982
0.0
-100.0
-200.0
-300.0
-400.0
-500.0
-600.0
-700.0
-800.0
-900.0
-1000.0
PRESSURE (MB)
250°K < TB(8) < 270°K
REGRESSION
SIMULTANEOUS
MODIFIED SIMULTANEOUS
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
TEMPERATURE RMSD (°C)

Figure 6

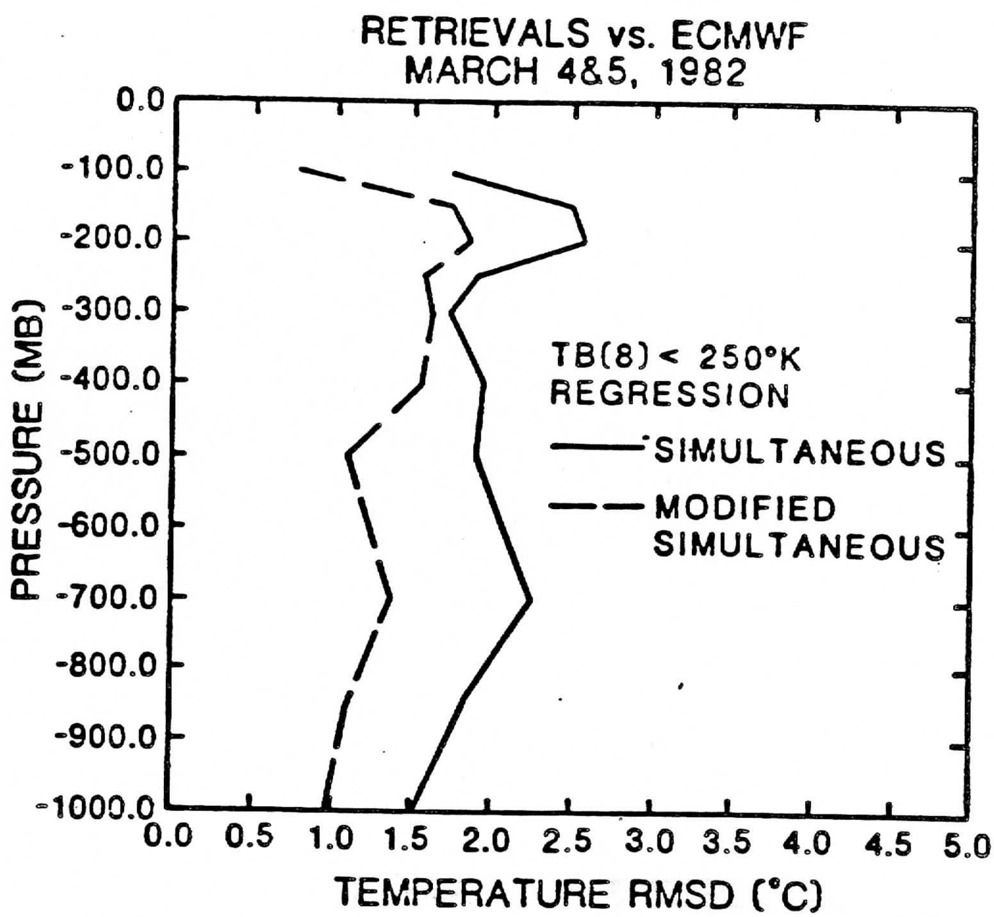

RETRIEVALS vs. ECMWF
MARCH 4&5, 1982
0.0
-100.0
-200.0
-300.0
-400.0
-500.0
-600.0
-700.0
-800.0
-900.0
-1000.0
PRESSURE (MB)
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
TEMPERATURE RMSD (°C)
TB(8) < 250°K
REGRESSION
SIMULTANEOUS
MODIFIED
SIMULTANEOUS

Figure 7

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